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Electronics Design of Avionics Hardware using Worst Case Analysis Techniques: An EMC Application and Example

Reinaldo J Perez

Electronic Products Reliability Group

Jet Propulsion Laboratory

California Institute of Technology

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Avionics Hardware for Space and The Space Environments

Avionics designers must contend with the space environment in the hardware design

Electronics designs and the resulting hardware are susceptible to the harsh space environment

Since EMC compliance in avionics hardware depends on good electronic design processes to control EMI, it is then obvious that the space environment can also play a role in EMC.

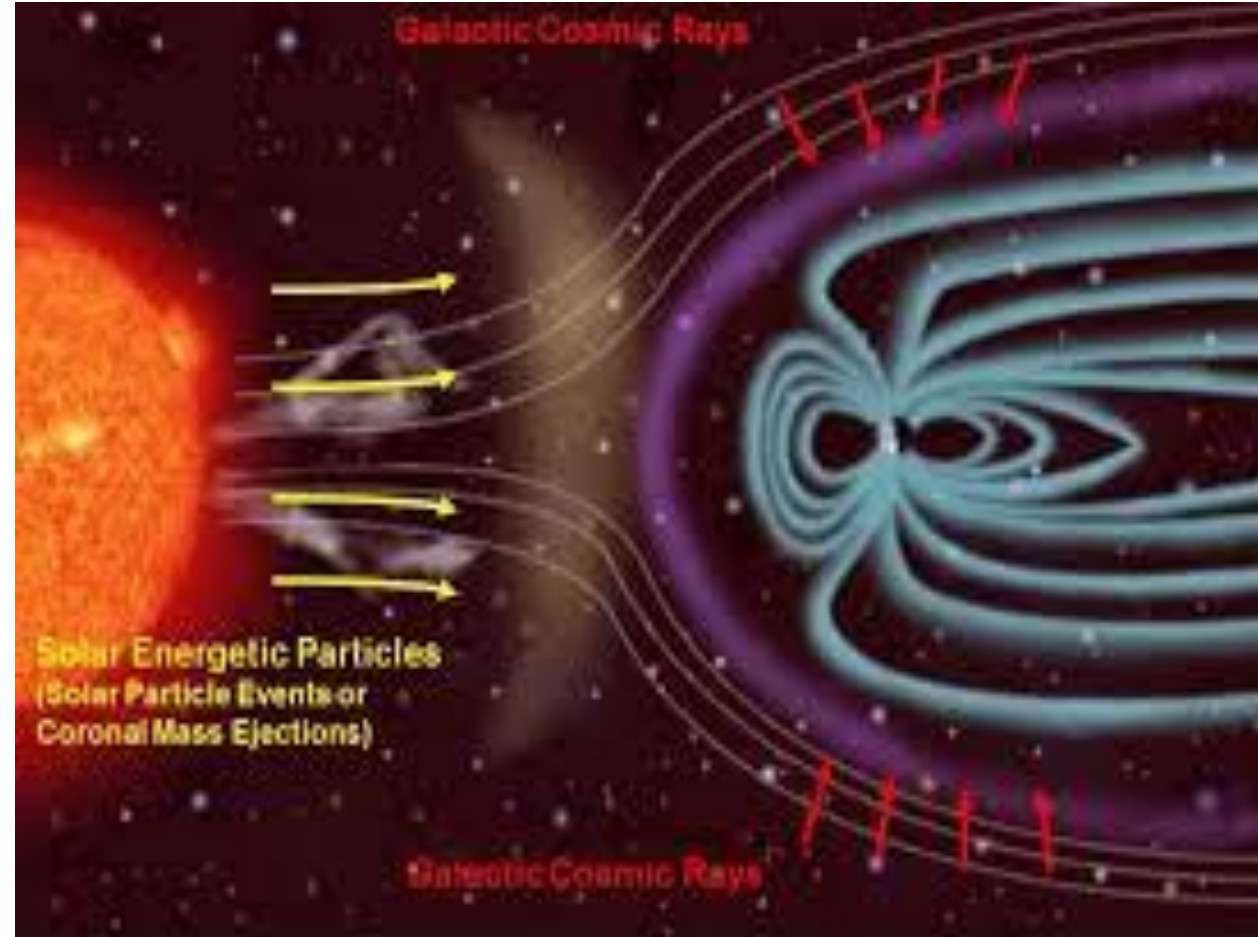
The three most important environmental factors that affect electronics are:

***Temperature:* -50°C to 150°C swings**

***Space Radiation:* Highly energetic charged particles (ions, electrons,...etc) which can affects electronic components performance.**

***Aging of Electronic Components:* Space missions are long term with no possibilities of repairs or maintenance**

Earth and the Space Charged Environment



Energetic charged particles from the sun and cosmos arrive to earth and are influenced by the earth magnetic field

The Space Environment and Electrical Components Parameters Variations

The space environments affect the performance of electrical components by changing components' parameter values. How component parameter values are affected depends on the type of electronic component. The table below shows electronic component type vs. principal source of parameter variation

Environmental Factor	Resistors	Capacitors	Diodes	BJTs	MOSFET	JFET	Dig. IC	Linear ICs	GaAs ICs
Temperature	X	X	X	X	X	X	X	X	X
Aging							X	X	
Radiation in (Rads)	>1Meg	>500K	>100K	>5K	>1K	>500K	>1K	>1K	>1Meg
Humidity	X	X							
Elec. Stress	X	X	X	X	X	X			
Mechanical	X	X							

The Space Environment and Electrical Components Parameters Variations (Cont.'s)

Each electrical component in avionic hardware has its own distinctive set of parameters that can be affected by the space environment and the table below shows a list of such parameters for each of the mostly used type of components.

Electrical Parameters	Resistors	Capacitors	Diodes	Inductor	BJTs	MOSFET	JFET	Dig. IC	Linear ICs	GaAs ICs
Resistance	X									
Capacitance		X								
Inductance				X						
Supply voltage								X	X	X
Input/Intrinsic Voltage(s)					X	X	X	X	X	X
Input/Intrinsic Current(s)			X						X	
Gain					X	X	X		X	
Output Voltage(s)								X	X	X
Output Current(s)			X							
Propagation Delay(s)								X	X	X
Timing Parameters								X	X	X

The Space Environment and Electrical Components Parameters Variations (Cont.'s)

Choosing the Electrical Components: One of the primary tasks for avionics design engineers is to develop an APPROVED components list for the design. The term “approved” means that the chosen components for the design must be first reviewed and then approved (or reject otherwise) after gathering empirical data, vendor data, and test data, and then make an assessment about the components’ reliability and tolerance fluctuations under worst case space environmental conditions.

An example addressing temperature tolerances:

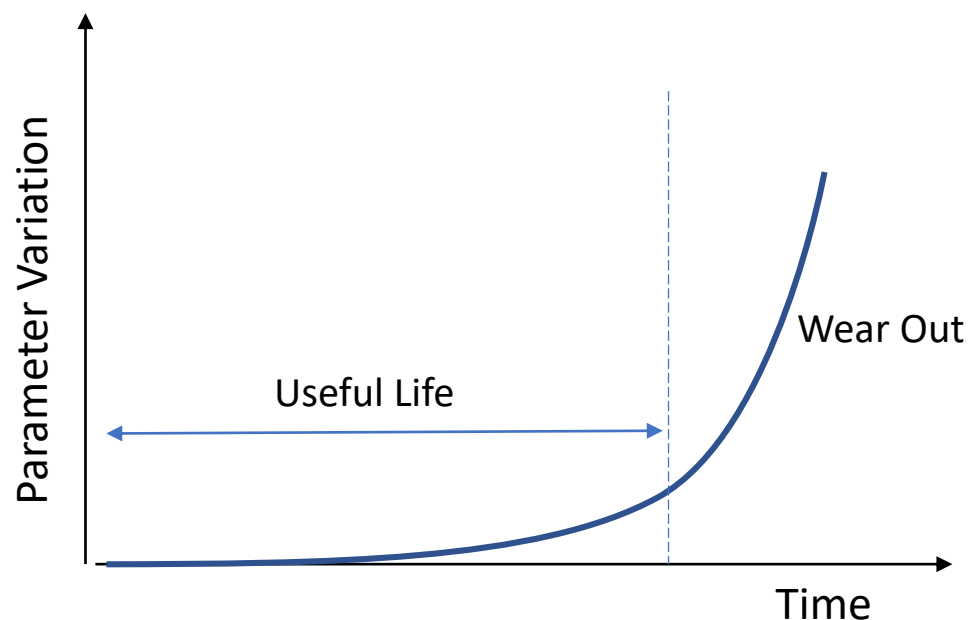
An EMI filter for a data interface contains a capacitor that is 20uF. The part has a tolerance of 10% at 25C. What would be the tolerance of that part, for a temperature fluctuation of -50C to 150C ?

The answer is (just for temperature alone!) 11.25% and -10.75% : Therefore, minimum capacitance = 17.85uF and maximum capacitance = 22.2 uF.

The “worst case” changes in capacitance means that you not longer have a 20uF in that EMI filter, hence the filter’s performance characteristics will change ! You must also address, in the same way, all the other components of the filter.

The Space Environment and Electrical Components Parameters Variations (Cont.'s)

Addressing Aging Effects: Electrical components which are powered are aging continuously. The aging is the result of chemical changes related to the relative energy levels of the reactants that make up the electrical components. These chemical changes causes parameters to drift.

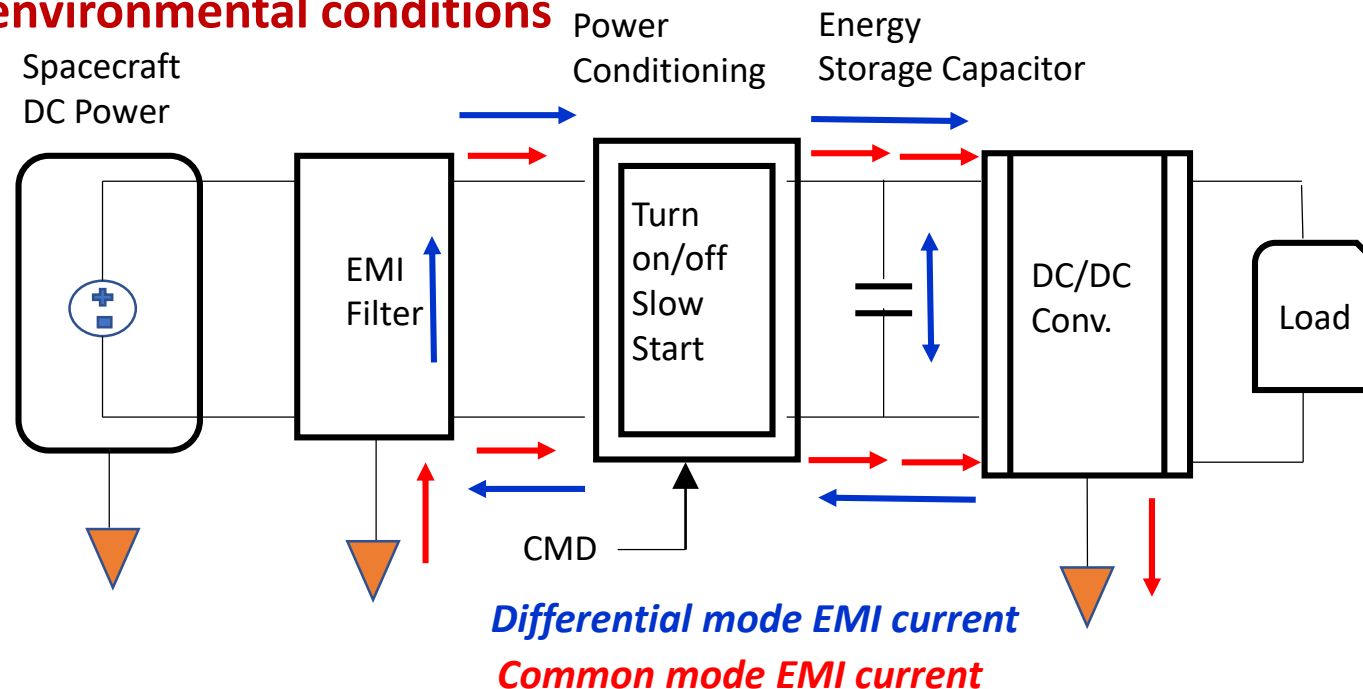


Let's consider the previous capacitor. The capacitor was tested for 200 hrs at 150C and this resulted in a change in capacitance of +/-15%. If this capacitor is used for 10 years at 85C, by how much the capacitance will change. The answer is +/- 3.75%. The overall change in tolerance for temperature and aging combined is: 15% worst case maximum and -14.5% worst case minimum.

Effects of Components Parameters Variations in EMC

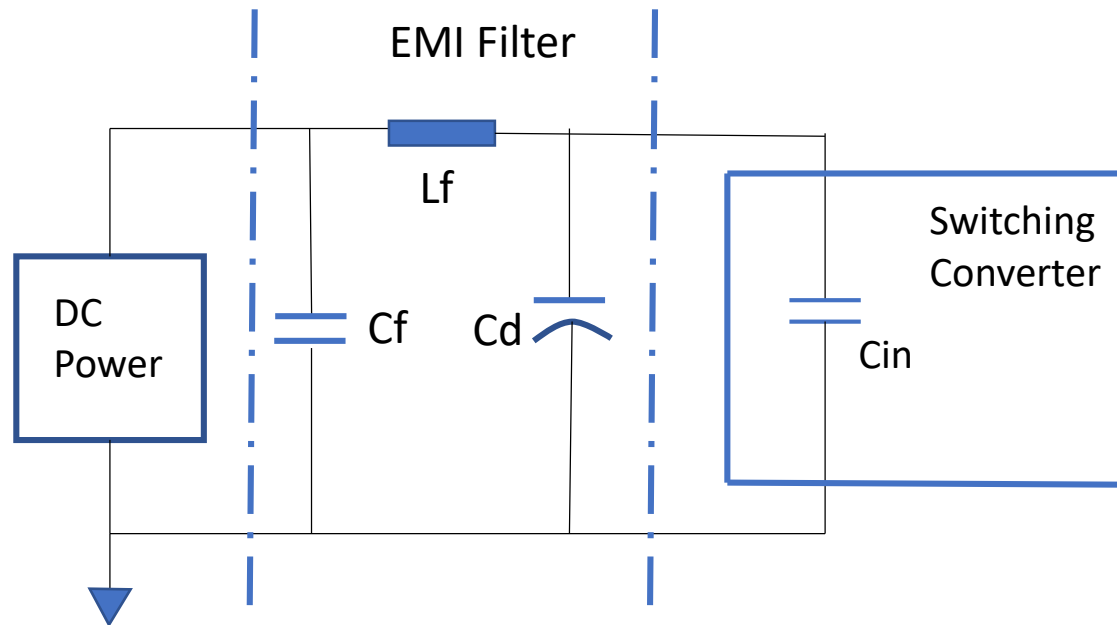
Before EMC principles are implemented in avionics hardware design, the same hardware must first be designed to survive the worst case environmental conditions, otherwise the EMC solutions will fall short.

Consider the EMI filter in the figure below. These filters are designed to attenuate differential and common mode noise produced by their respective currents (shown in figure) and are designed to attenuate such noise by as much as 80 dB/decade over a frequency range beyond cut-off frequency. In order to accomplish this the EMI filter must be designed such that it will perform such functions under worst case space environmental conditions



Designing an EMI Filter for a Switching Converter

Let's consider the design of a LP EMI filter for a switching converter. The filter must attenuate EMI noise to at least 65 dbuV. The input capacitance of the switching converter is $C_{in}=20\mu F$. The switching frequency of the converter $F_s=800$ kHz. The input voltage from the power supply $V_{in}=30V$ and the output voltage from the switching converter is $V_{out}=3.3V$. The maximum output current of the converter is $I_{out}=3A$. The estimated noise level (measured data) of the switching converter is 120dBuV (ripple voltage). The filter is shown below (in its simplest form, also known as *parallel damping LC*). The required attenuation (Att) in dB is $120-65= 55$ dB



Designing an EMI Filter for a Switching Converter

The inductor L_f defines the resonant frequency. For low current applications (3A is a low current application) L_f should be between 1uH to 10uH (usually). Let's choose 1uH. We now calculate C_f . The C_f capacitance is constrained by two capacitance C_{fa} and C_{fb} , as shown below:

$$C_{fa} = \frac{C_{in}}{\left(C_{in} * L_f * \left(\frac{2\pi F_s}{10} \right)^2 - 1 \right)} \quad (1)$$

$$C_{fb} = \frac{1}{L_f} * \left(\frac{10^{\frac{Att(dB)}{40}}}{2\pi F_s} \right)^2 \quad (2)$$

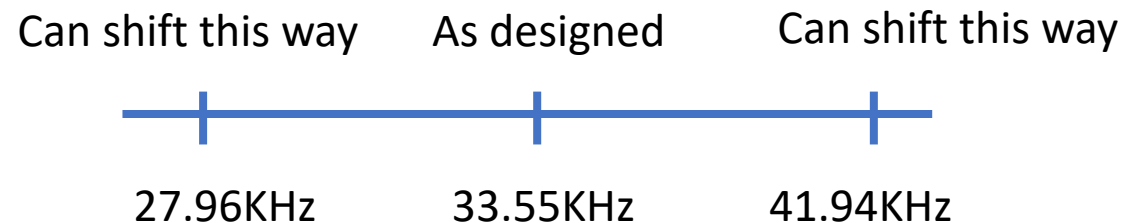
The first formula for C_{fa} ensures that the resonance frequency of the EMI input filter is at least one decade below the switching frequency F_s . The second formula for C_{fb} is derived from an approximation that ensures proper attenuation of the EMI filter (in this case we want 40 dB attenuation per decade per equation 2). Select the higher value of C_{fa} and C_{fb} because both conditions must be met. In the above formulas, F_s is in kHz, C_{fa} & C_{fb} are in uF and L_f is in uH. The results are $C_{fa}=2.96\mu F$, $C_{fb}=22.5\mu F$. Therefore, $C_{fb}=C_f=22.5\mu F$.

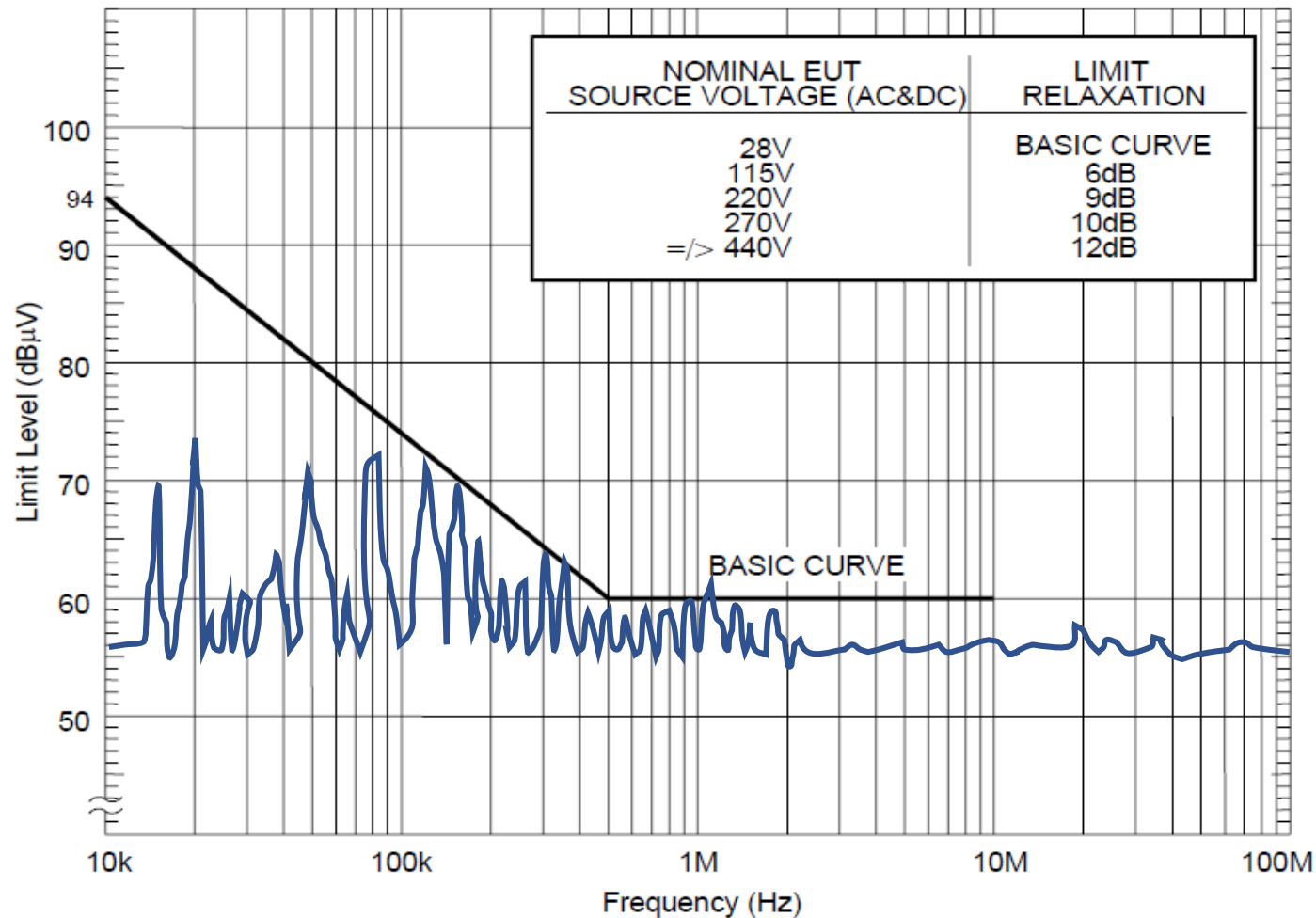
Designing an EMI Filter for a Switching Converter

The cut off frequency F_c of the low pass filter (LPF) is $1/2\pi\sqrt{L_f \cdot C_f} = 33.55 \text{ kHz}$. The capacitor C_d is a tantalum capacitor with ESR. C_d is a damping capacitor and the damping is needed because the EMI output impedance can be very high at the resonance frequency (i.e. the Q of the LPF formed by C_{in} and L_f can be very high). The value of C_d should be greater than $4 \cdot C_{in}$. So in our case it should at least be $4 \cdot 20\mu\text{F} = 80\mu\text{F}$. The ESR of the chosen capacitor can be around from $\sqrt{L_f/C_{in}} = 112 \text{ milli-ohms}$. The purpose of the ESR is to reduce the peak output impedance at F_c of the LPF. The C_d blocks the dc component of the input voltage and avoids excessive power dissipation on ESR.

Let's assume now that C_f and L_f change by 20% due to space environmental conditions. This means that the cut off frequency of 33.55 kHz can fluctuate between $F_{c_min} = 27.96 \text{ kHz}$ and $F_{c_max} = 41.94 \text{ kHz}$.

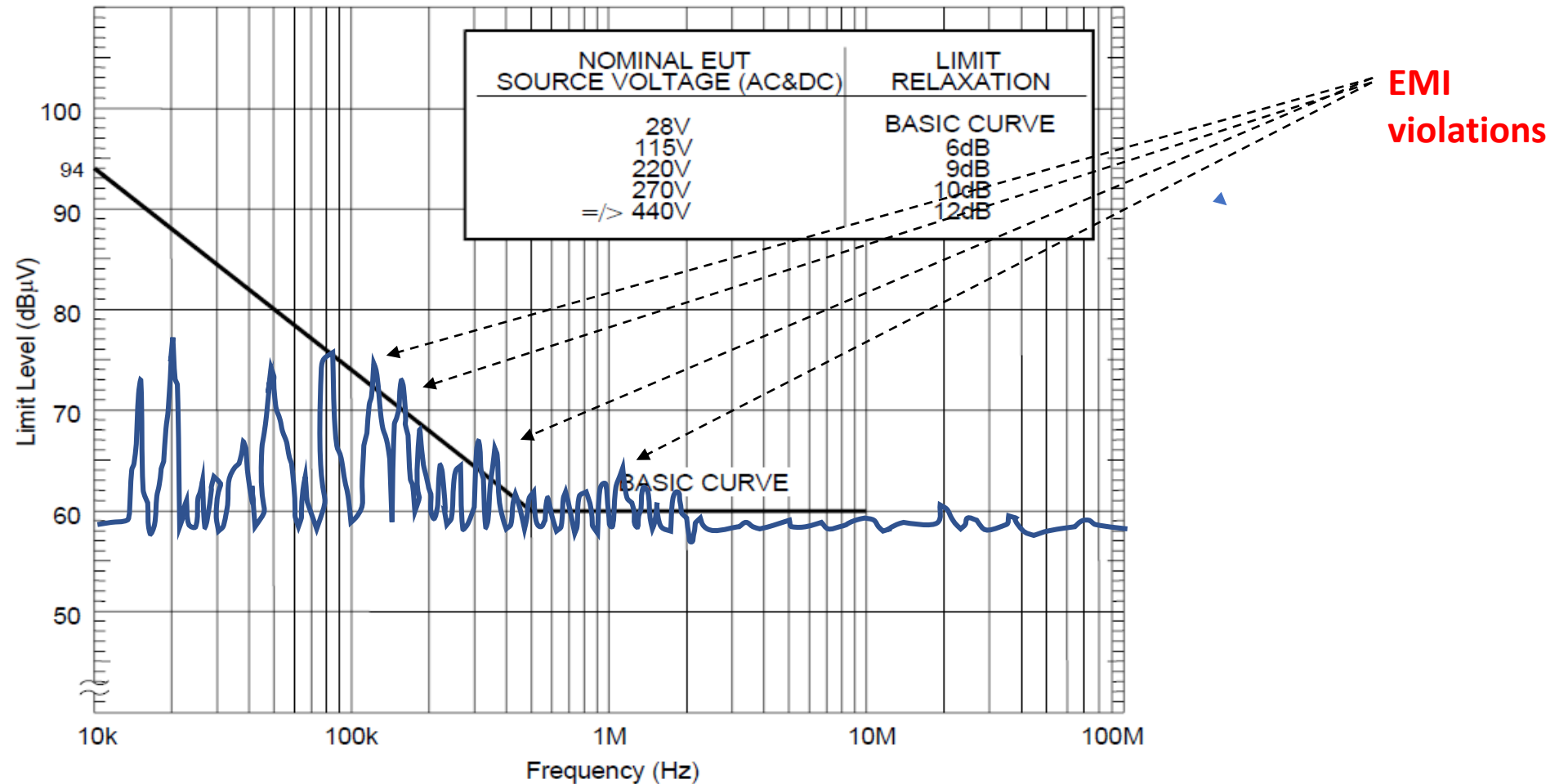
What does this mean from an EMI point of view? It means that the “damping” capability of the EMI filter to diminish ripple noise will be shifted as time goes by and under worst case environmental conditions.





At the beginning of life (BOL) of its application, the EMI Filter, as originally designed, performs well in controlling EMI Emissions.

FIGURE CE102-1. CE102 limit (EUT power leads, AC and DC) for all applications.

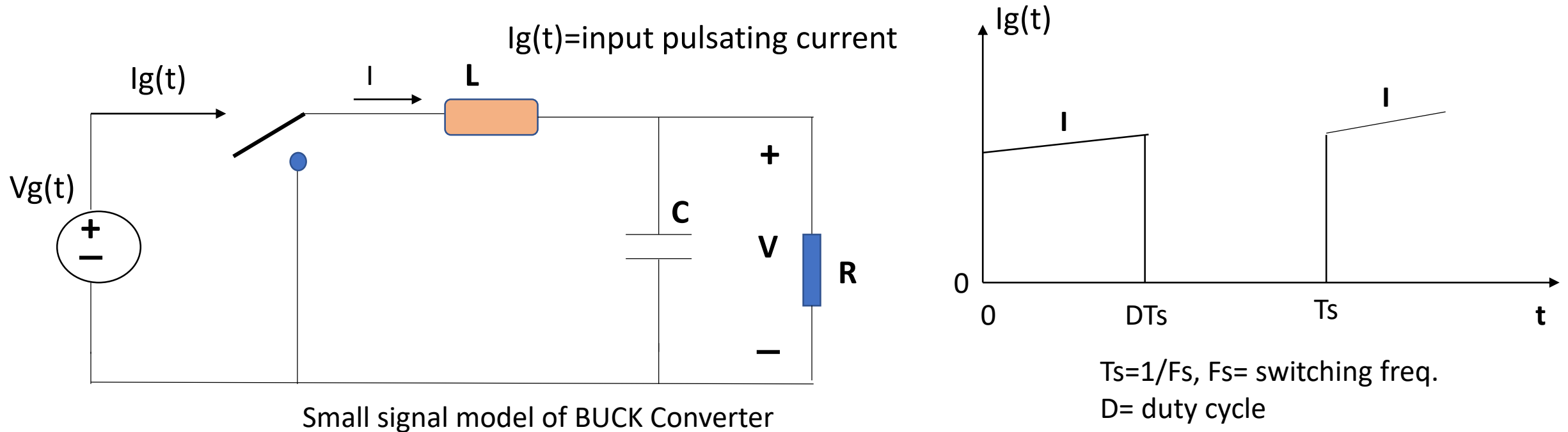


At the end of life (EOL) of its application, the EMI Filter, as originally designed, NO LONGER performs well in controlling EMI Emissions.

FIGURE CE102-1. CE102 limit (EUT power leads, AC and DC) for all applications.

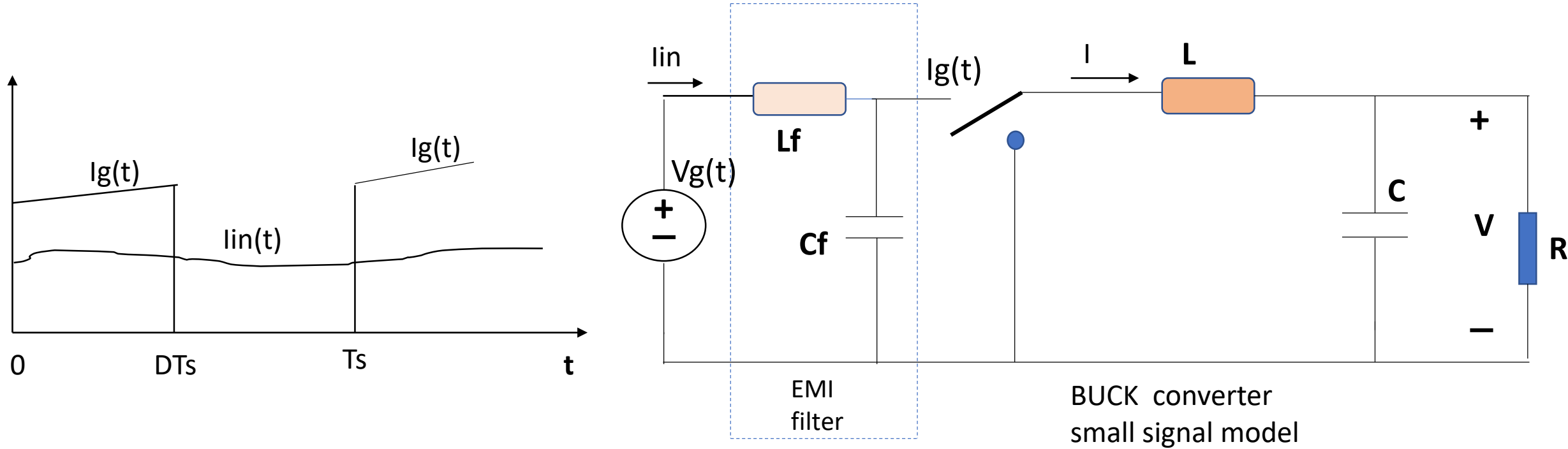
Though EMI violations may not be a big issue, we need to go beyond than just looking at EMI noise and explore the overall effect of parameters variations of EMI filter design. Therefore, let's consider the ensemble of the EMI filter couple with a switching power converter.

Let's consider an actual application. We start with some simplified theory on converter design. We choose the Buck converter:



The Fourier series of $I_g(t)$ is: $I_g(t) = DI + \sum_{k=1}^{\infty} \frac{2I}{k\pi} \sin(k\pi D) \cos(k\omega t)$. High frequency current harmonics of large amplitude are injected back into $V_g(t)$ source

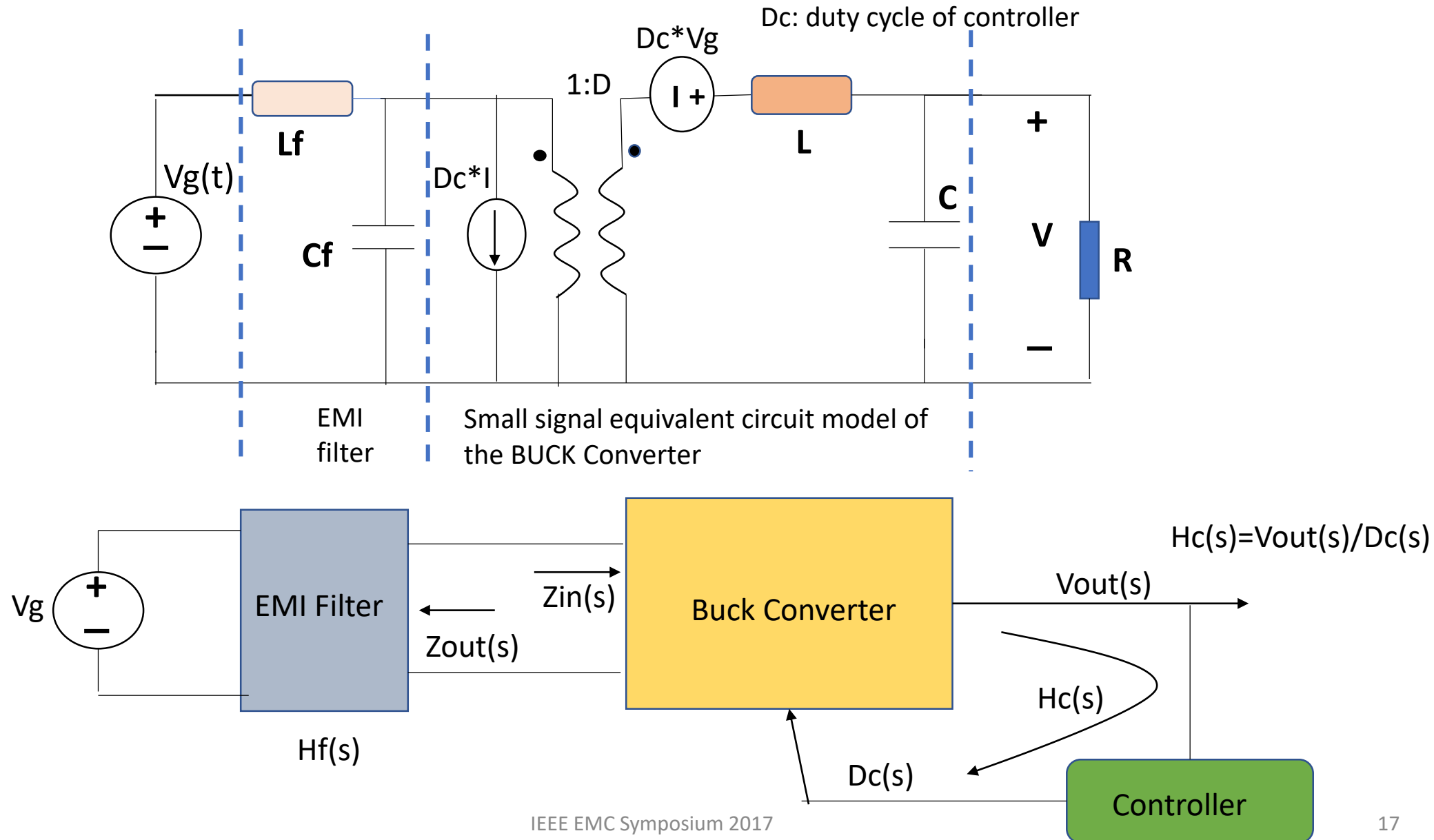
Adding a low Pass EMI to the Converter Filter



Magnitude and phases of the input current harmonics are modified by input filter transfer function $H(s)$:

$$i_{in}(t) = H(0)DI + \sum_{k=1}^{\infty} \|H(kj\omega)\| \frac{2I}{k\pi} \sin(k\pi D) \cos(k\omega t + \angle H(kj\omega))$$

Effect of an Input EMI Filter on Converter Transfer Function



Effect of an Input EMI Filter on Converter Transfer Function (Con't)

We now can state the overall transfer function for the output of the Buck converter. Using the previous diagram we get.

$$H_{cs}(s) = H_{cs}(s)_{original} * \frac{\left(1 + \frac{Z_{out}(s)}{Z_{in}(s) \text{ at } D_C(s) = 0}\right)}{\left(1 + \frac{Z_{out}(s)}{Z_{in}(s) \text{ at } V_{out}(s) = 0}\right)}$$

where:

$H_{cs}(s)_{original}$ is the transfer function of the buck converter before adding the input filter

$Z_{out}(s)$ is the output impedance of the EMI filter

$Z_{in}(s)$ at $D_C(s)=0$ is the converter input impedance when we set the input of the controller to zero

$Z_{in}(s)$ at $V_{out}(s)=0$ is the converter input impedance when was short out the output

Notice now how the overall transfer function depends on the EMI filter output impedance!

Effect of an Input EMI Filter on Converter Transfer Function (Con't)

Therefore, if we want the converter output impedance NOT to be substantially affected by the EMI input filter, the following conditions must be satisfied:

$$\|Z_{out}(s)\| \ll \|Z_{in}(s) \text{ at } Dc(s) = 0\|$$

$$\|Z_{out}(s)\| \ll \|Z_{in}(s) \text{ at } Vout(s) = 0\|$$

The above expression now becomes a design criteria.

In the same manner if:

$$\|Z_{out}(s)\| > \|Z_{in}(s) \text{ at } Dc(s) = 0\|$$

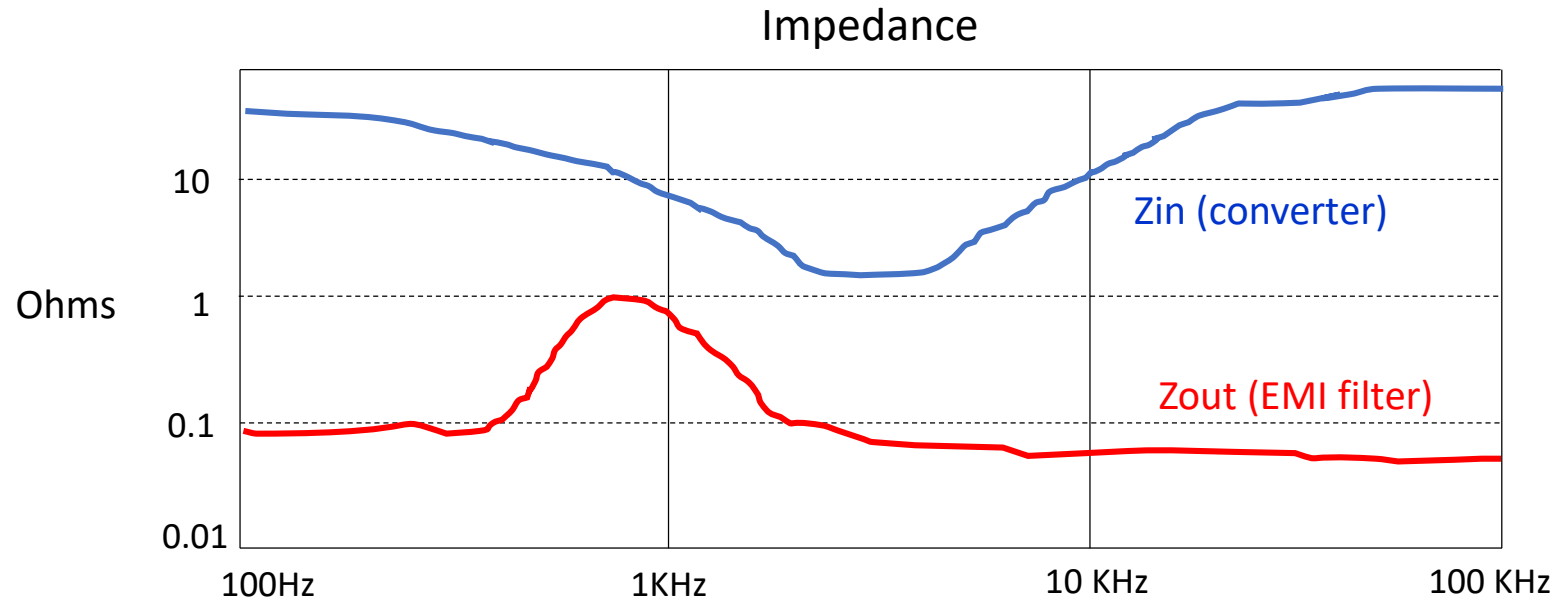
$$\|Z_{out}(s)\| > \|Z_{in}(s) \text{ at } Vout(s) = 0\|$$

The design of the converter becomes unstable.

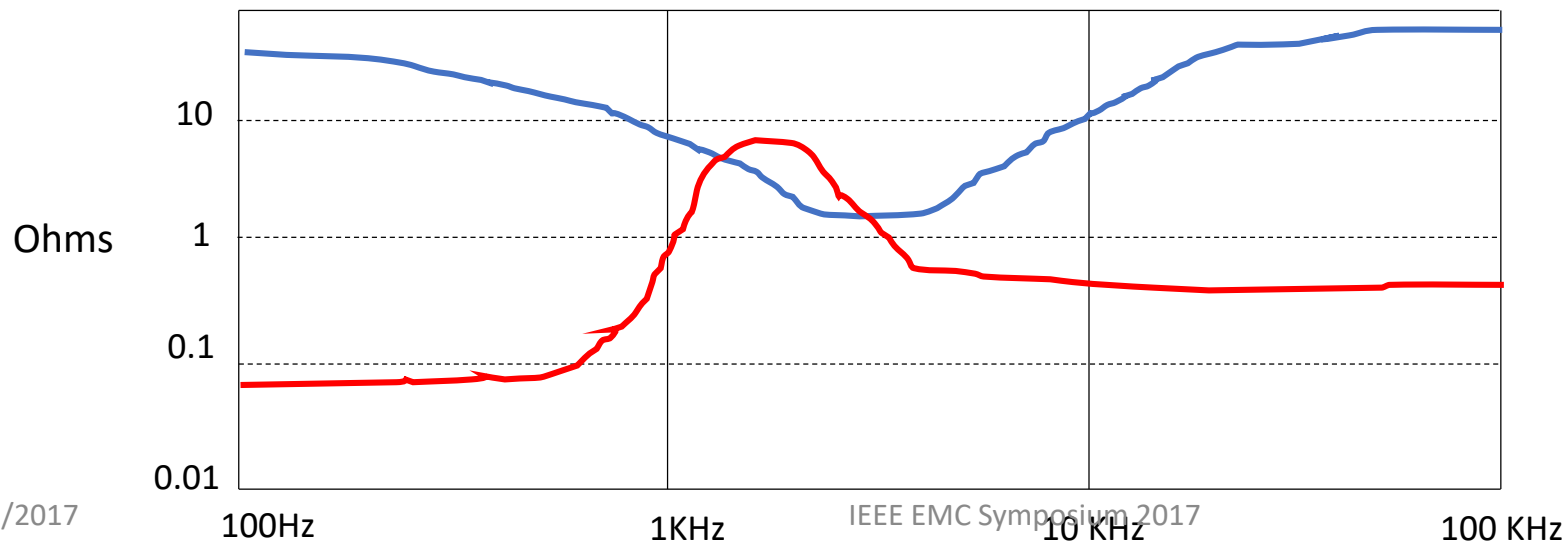
Therefore the design of the EMI filter has a direct impact in the stability of the converter!

Effect of an Input EMI Filter on Converter Transfer Function (Con't)

So what does all that means ? The best way is to present this pictorially



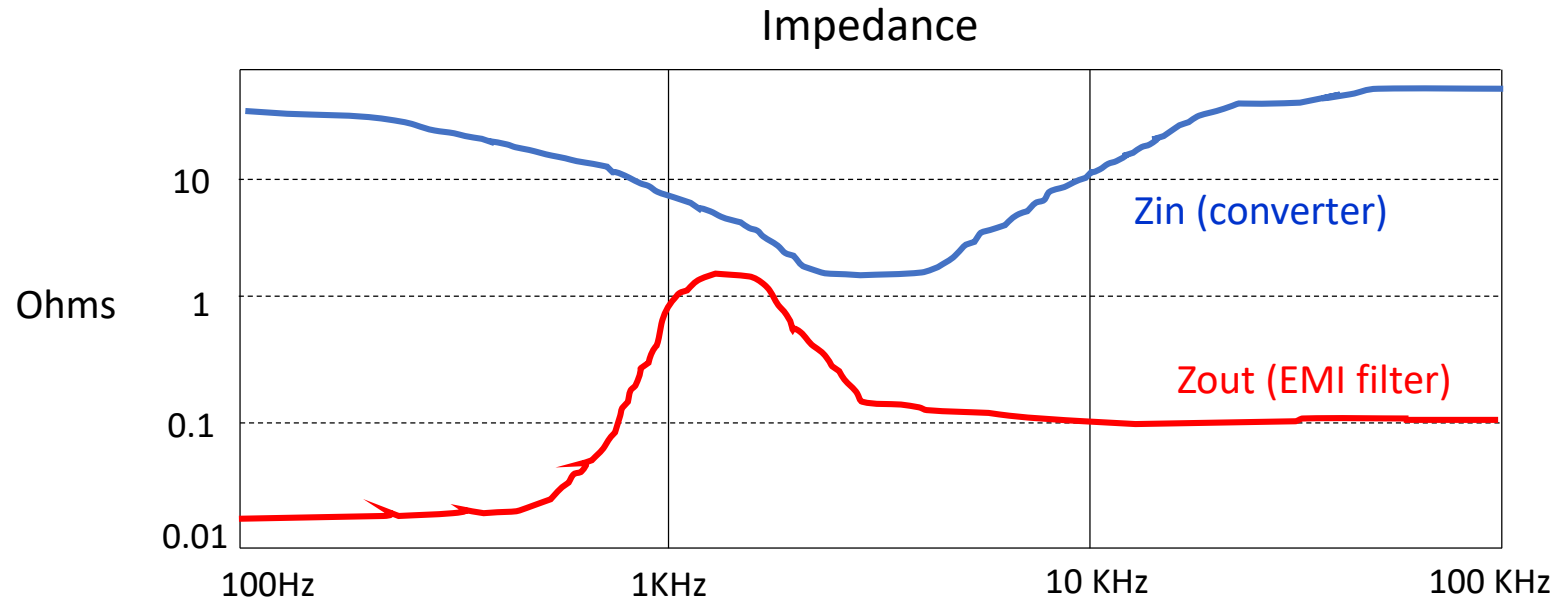
Good EMI Filter design
 $Z_{out} \ll Z_{in}$ at all frequencies



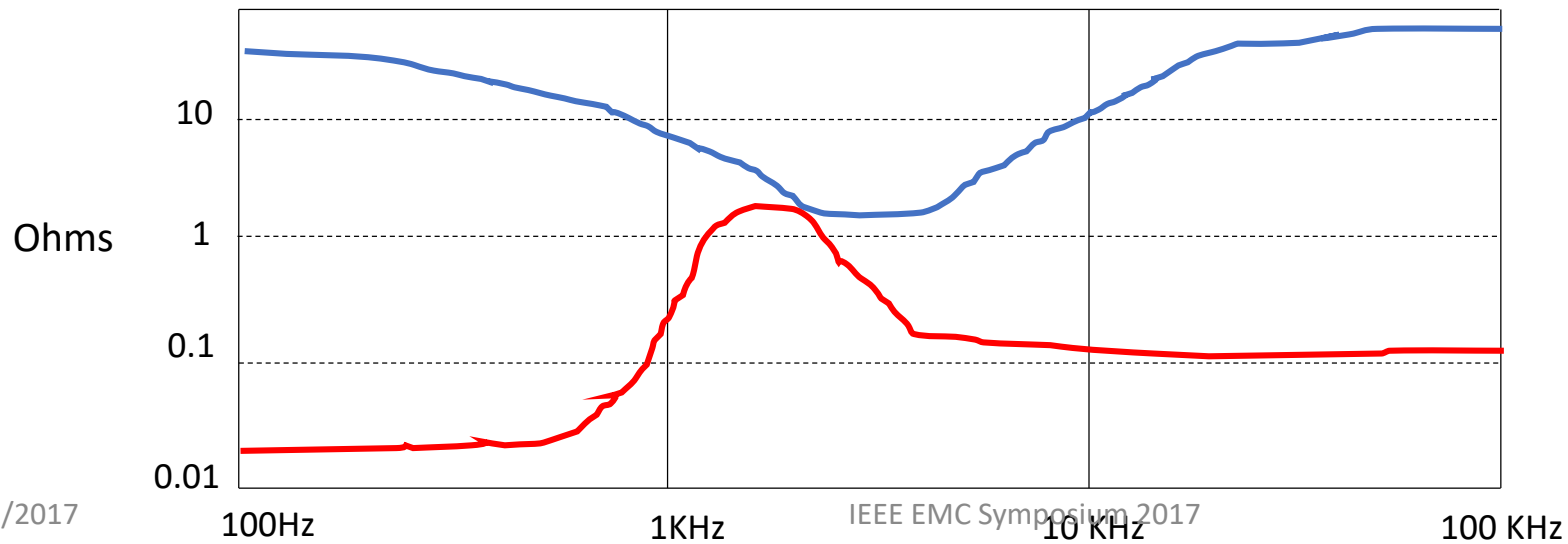
Bad EMI Filter design
 $Z_{out} > Z_{in}$ at 3-5 KHz
Converter is unstable.

Effect of an Input EMI Filter on Converter Transfer Function (Con't)

An EMI Filter Z_{out} will change over time due to environmental effects, and can cause problems at EOL

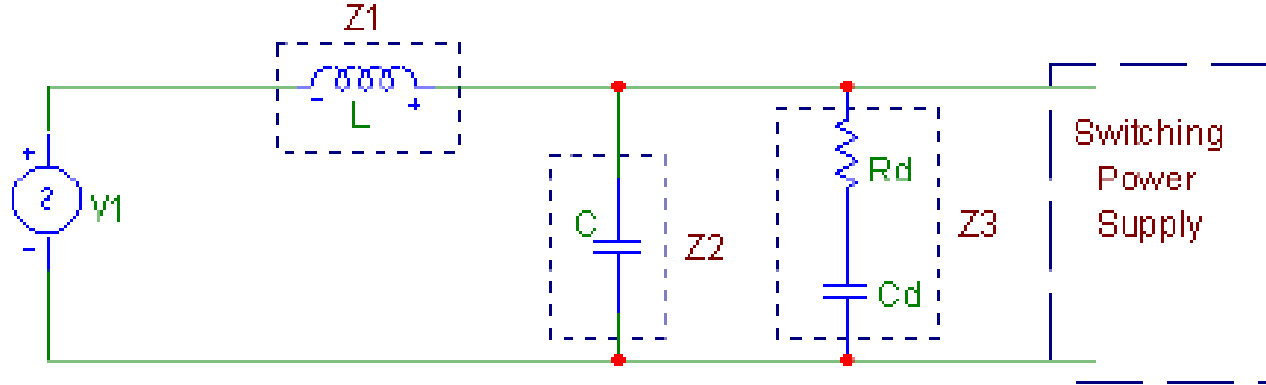


EMI Filter Z_{out} at BOL
 $Z_{out} < Z_{in}$ at all frequencies

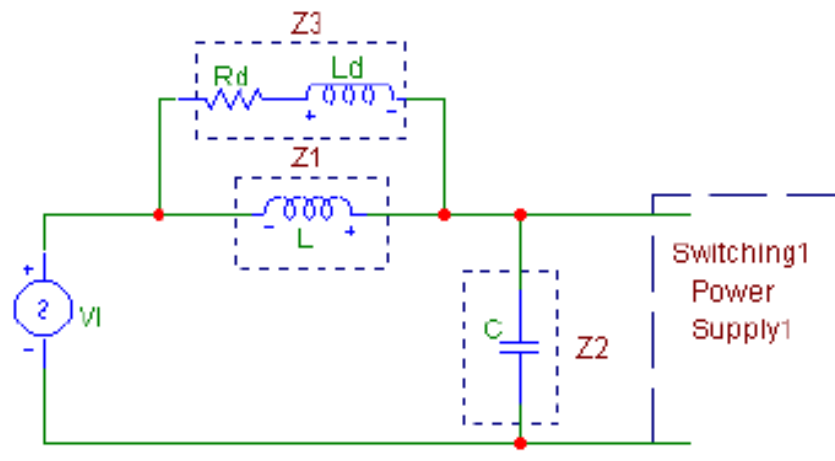


EMI Filter Z_{out} at EOL
(resonance has shifted)

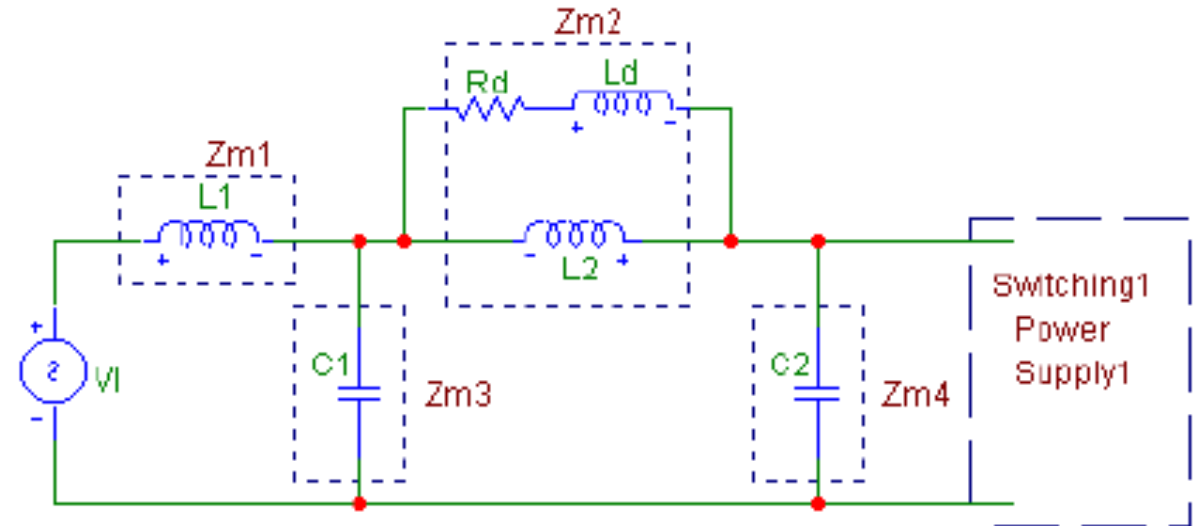
Types of Typical EMI Filters



Parallel Damped Filter

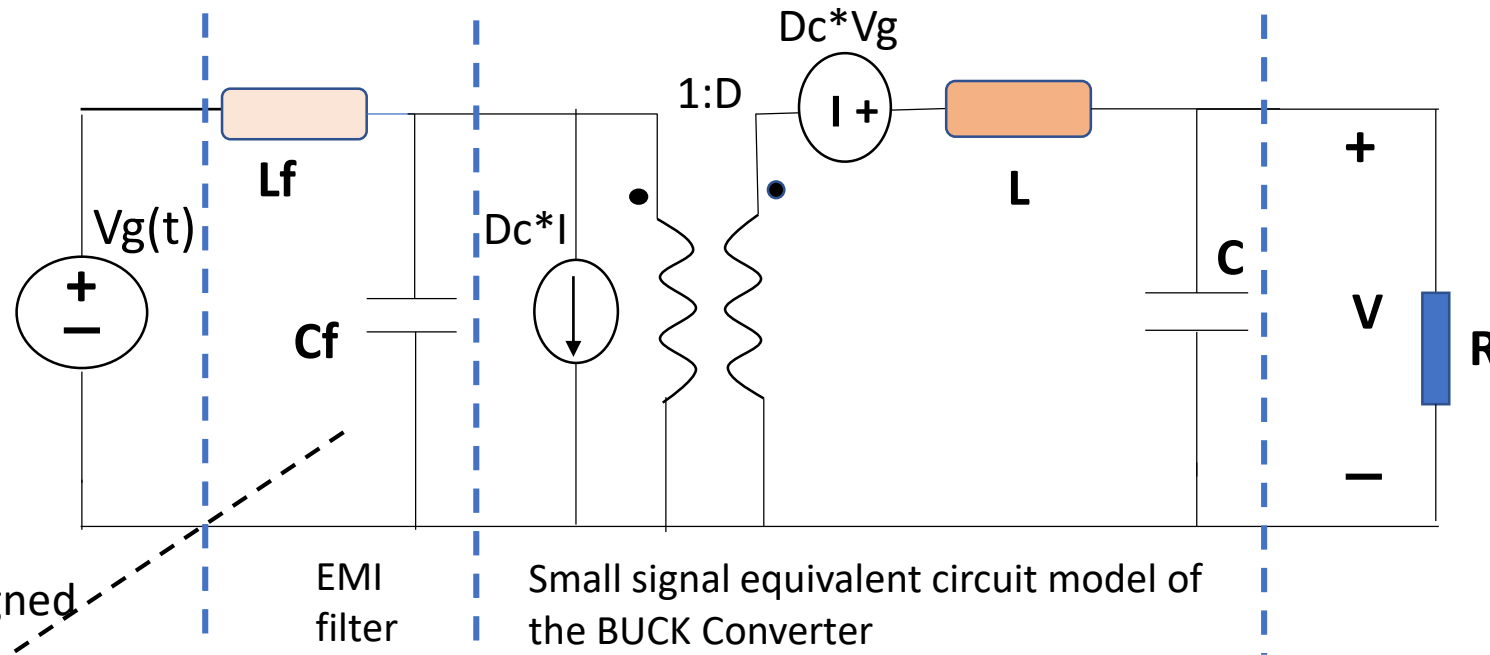


Series Damped Filter
(good at LF not so good at HF attenuation)



Two-Section Input Filter
(allows higher attenuation at HF and uses smaller values of components. Reduce cost)

Analysis Example



$$D=0.5$$

$$I=1A$$

$$D_c=0$$

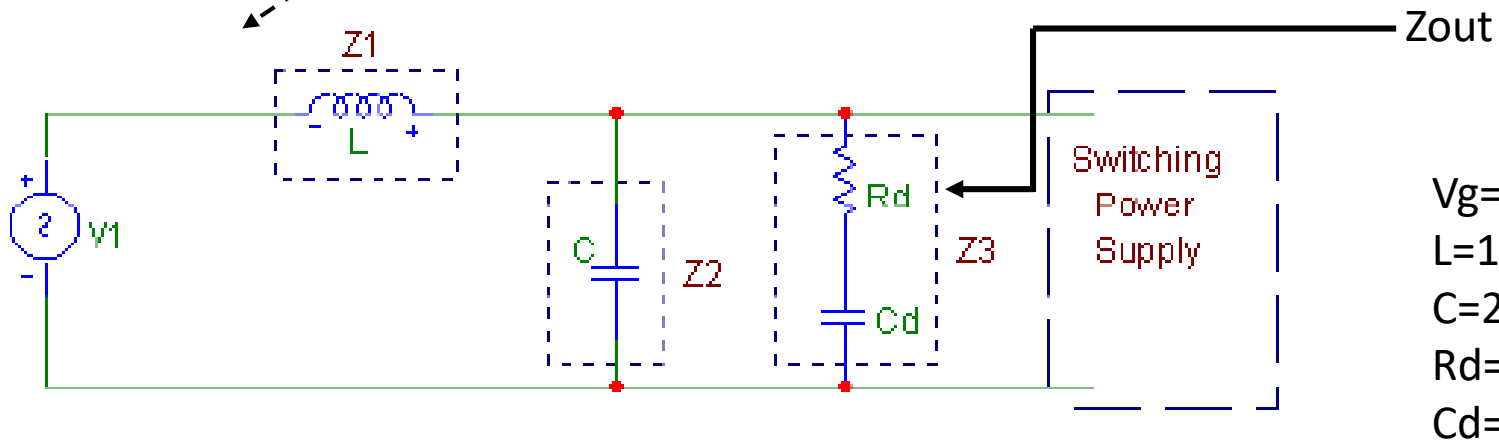
$$L=100\mu H$$

$$R=3 \text{ ohms}$$

$$C=100\mu F$$

Simulate Z_{in}

Use our previously designed parallel damped filter



$$V_g=28V$$

$$L=1\mu H$$

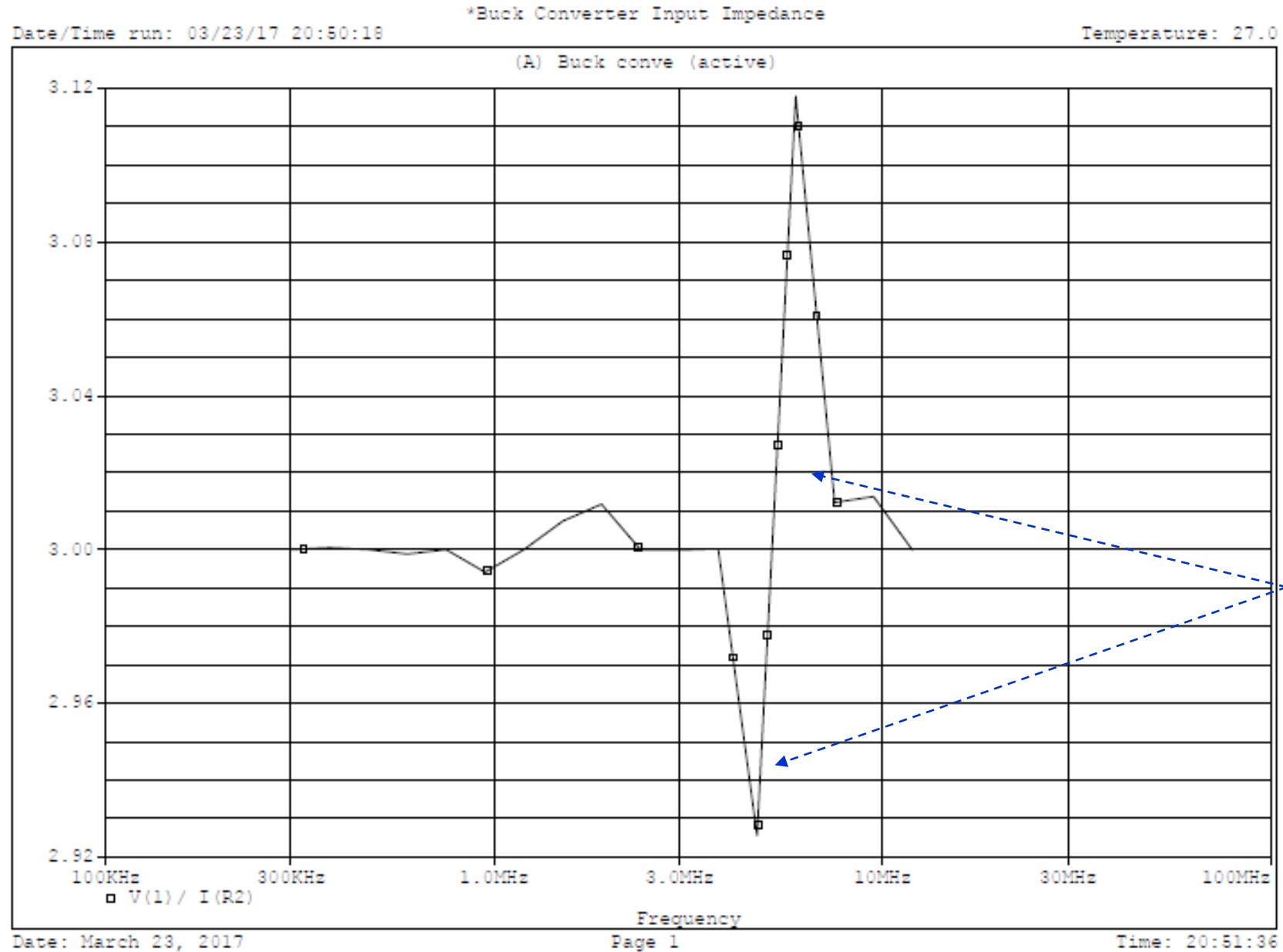
$$C=22.5\mu F$$

$$R_d=0.112$$

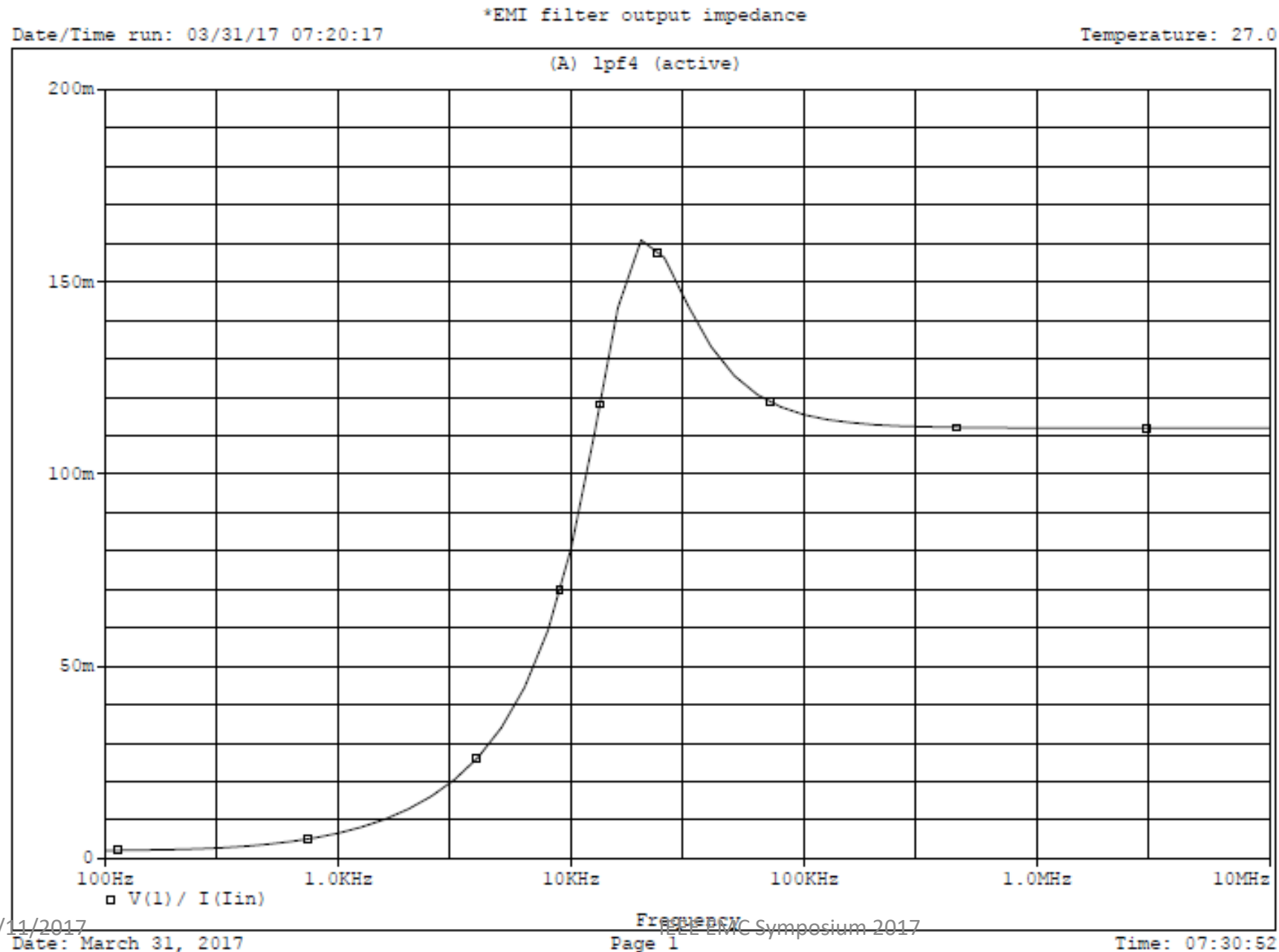
$$C_d=80\mu F$$

(This is the EMI filter we previously designed)

Zin: Input Impedance of Converter



Zout: Output Impedance of EMI Filter



Resonance occurs at within 20-35 kHz. Well below the resonance frequencies for the converter . Also $Z_{out} < Z_{in}$ at all frequencies.

Conclusion: Very good design of EMI filter. Even if there are large worst case variations in components parameters for the filter. The EMI filter will perform well till EOL.

Conclusions

In aerospace systems electronics are exposed to extreme environmental effects. It is important to assess how such environmental effects can affect the design and the performance of aerospace electronics, including aerospace electronics hardware that has been designed to control EMI. In general EMC assurance can be compromised during long missions if efforts are not spent first in addressing extreme environmental effects during the design phase of electronics hardware.

An example of these environmental effects was addressed in the design and use of an EMI filter and two crucial aspects were discussed: the capability of the EMI filter to suppress noise, and the role that the EMI filter plays in the stability of the power converters.